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6. AUTHOR(S)

Professor Aharon Katitulnik
Professor Theodore H. Geballe

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Department of Applied Physics
Stanford University
Stanford, CA 94305

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FINAL TECHNICAL REPORT

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FABRICATION AND ANALYSIS OF JOSEPHSON AND WEAK-LINK JUNCTIONS AND ARRAYS

Aharon Kapitulnik, Professor

Principal Investigator

Theodore H. Geballe, Professor

Co-Principal Investigator

Department of Applied Physics

Stanford University

Stanford, California 94305

August 1992

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I. General

The work took two main avenues in order to prepare the ground for the main goal of the program: planar junctions made with the use of scanning tunneling microscope and atomic force microscopes in conjunction with some novel ideas of etching and metal deposition. The first avenue was the fabrication of ultra small bridges on which junctions will be written. The second avenue was a theoretical analysis of a single junction as well as arrays of many sections of that type.

The termination of this program did not allow us to bring the two parts together.

I.1 Fabrication and Behavior of Ultrasmall Superconducting Structures

Our interest is in the field of ultra small superconducting structures. In particular, we want to examine the behavior of coherent vortex flow structures made out of the high temperature superconductor $YBa_2Cu_3O_7$.

Theory predicts that microbridges whose length and width are less than the penetration depth, but larger than the coherence length, will exhibit coherent vortex flow[1]. Our interest in such coherent vortex flow structures is two-fold. First, the behavior of such devices has mainly been examined theoretically, not experimentally, so it is desirable to confirm our present understanding. Second, these devices have the potential to be exploited in electronic circuits.

We have chosen to work with the high temperature superconductor $YBa_2Cu_3O_7$ for two reasons. First, YBCO has a larger penetration depth (>1500Å) than many superconducting materials, making it possible to fabricate coherent vortex flow structures. Second, it has proven very difficult to make conventional tunnel junctions out of the high temperature copper oxide superconductors, so alternative structures for electronic applications may be necessary.

Our goals may be summarized as follows:

(i) Develop a fabrication process capable of patterning YBCO films down to deep sub-micron dimensions, with minimal damage.

(ii) Test these microbridges for the expected vortex flow behavior and reconcile our results with theory if necessary.

(iii) Examine possibilities for electronic applications.

Referenccs

1) "Vortex Motion and the Josephson Effect in Superconducting Thin Bridges", K. K. Likharev, Soviet Physics JETP, Vol. **34**, Number 4, April 1972.

2) Alternative fabrication techniques include:
- focused ion beam direct write etching
I. D. Zitkovsky et al, APL **59** (6), 5 Aug. 1991, pg. 727
-liftoff of amorphous YBCO film then post anneal
S. E. Romaine et al, APL **59** (20), 11 Nov. 1991, pg. 2603

I.2 Magnetic control characteristics of planar Josephson junctions

There are two generic geometries of Josephson junction devices - sandwich-type and planar-type- as illustrated in Figure 2. The current low-temperature superconducting electronic technology is based on tunnel junctions in the sandwich geometry. However, at present the only useful Josephson junction devices made from the high-Tc superconductors (grain boundary junctions) have the planar geometry. In this program we have been seeking to develop Josephson devices with the high-Tc superconductors in the form of nanoscale microbridge Josephson junctions. These are also of the planar type. In actual operation, all Josephson devices are controlled by the application of magnetic field. Detailed theories of the magnetic response of sandwich-type junctions exist. By contrast, the planar case has received very little attention. More important, considerable magnetic control data

(specifically so-called magnetic diffraction patterns associated with superconducting quantum interference in the junctions) have been reported that exhibit behavior inconsistent with current device theories developed for the sandwich geometry. Motivated by these results and the needs of our own program, we have undertaken the development of a theory of the magnetic control characteristics of planar Josephson devices.

The key difference in the sandwich and planar devices is the radically different local magnetic field pattern in the two cases. In particular, in the planar case it is necessary to take into consideration the considerable field penetration into the electrodes of the device, as well as simple demagnetization factor effects. By calculating the magnetic field patterns expected in planar devices using the London theory of superconductivity, we have been able to account for the observed control characteristic data. In particular, we have been able to account for the very different dependence of the control characteristics on the width of the device - proportional to w for sandwich-type devices and proportional to w^2 for planar devices. This work thus both resolves an experimental anomaly and represents an important first step toward a detailed device physics model of planar Josephson devices. A paper describing this work has been published in *Applied Physics Letters.*

I.3 Physics of Two Dimensional Josephson Junction Arrays of High Tc superconductors: Studies in the Thermodynamics of two-Dimensional vortex lattices

Two dimensional arrays of Josephson junctions can be described in terms of the x y model of statistical mechanics. When placed in a magnetic field, such arrays become "frustrated" in that phase change around a primitive plaquette of the lattice can become a non-integer multiple of 2p . Such frustrated arrays were studied by a number of authors including Choi and Doniach (Reference 1). One way to represent such a frustrated array is in terms of a vortex lattice. At finite temperatures, a two-dimensional vortex lattice was first shown to have a melting transition by Huberman and Doniach (Reference 2).

An additional complication which can arise in arrays made of high Tc superconductors is that because the high Tc material itself is very strongly type II, lattices of this type may be expected to have vortices trapped inside the junction elements in addition to the vortices defined by the array itself. This problem has been recognized in magnetic studies of ceramic high Tc materials where it is found that vortex trapping in the high Tc grains can very strongly bias the properties of the array of weak links constituted by the ceramic structure of the material (for a study of magnetic properties of a very idealized model of a weak link array, see Ceccatto et al, Reference 3).

For this reason we decided to start a theoretical study of uniform two-dimensional high Tc films with a view to extracting working parameters which could be applied to a Josephson junction array made out of high Tc elements.

Our idea here was to model the statistical mechanics of the vortex lattice in terms of vortex variables as opposed to a simulation in which every elementary unit cell is given a phase and amplitude which are varied statistically. The reason for this is that in uniform high Tc samples the typical elementary length, the Ginsburg-Landau coherence length, is on the scale of 10-20 angstroms while the array elements may be microns in extent. Therefore, the traditional modeling of Josephson arrays in which each superconducting element is represented by a single phase and amplitude variable is not applicable when trapping of flux within the junction elements becomes an important issue.

As a spin-off from this work, we have applied the above method to look at the thermodynamics of three-dimensional high Tc crystals. In this approach, the representation of a vortex lattice is as a set of two-dimensional vortex dynamical variables coupled through "interlayer" strings as discussed in Reference 4. This study of three-dimensional vortex lattice melting has been published by Ryu et al. (Reference 5).

References

1. M. Y. Choi and S. Doniach, Phys. Rev. B **31** 4516 (85).

2. B. Huberman and S. Doniach, Phys. Rev. Lett. **43** 950 (79).

3. A. Ceccatto, S. Doniach, K. Frahm, and B. Muhlschlegel Z. Phys. B. **82** 257 (91).

4. S. Doniach in "High Temperature Superconductivity --The Los Alamos Symposium 1989" K Bedell et al. eds. Addison Wesley 1990, p. 406.

5. S. Ryu, S. Doniach, and G. Deutscher and A. Kapitulnik, Phys. Rev Lett. **68** 710 (92).

II. Accomplishments

1. The work we have done so far has concentrated on solving fabrication problems. Making YBCO nanostructures has proven to be an especially challenging task, because the superconducting properties of YBCO can be easily degraded by many process steps. Nevertheless, we have now succeeded in developing a process suitable for making superconducting YBCO microbridges with length and width dimensions as small as Å.

Our process for making submicron YBCO microbridges is:

(i) Electron beam lithography performed on a YBCO wafer coated with negative resist.

(ii) Transfer of the resist pattern onto the YBCO wafer via Ar ion milling.

(iii) Establishment of electrical contact to the devices on the wafer via an optical lithography step. Au evaporation, and lift-off.

Preliminary results indicate that the damage to the YBCO after this process is limited to a reduction in Tc by only a few degrees K. Further investigation is needed to show how much below 1000Å one can make YBCO microbridges and not suffer excessive damage.

The enclosed picture shows a microbridge 0.5 μm wide by 1.0 μm long patterned using this method. The smallest such microbridges we have made have been 0.125 μm wide by 0.25 μm long.

2. Development of a theory of the magnetic control characteristics of planar Josephson devices. The different dependence of the control characteristics in the width of the device was calculated and the experimental anomoly was resolved.

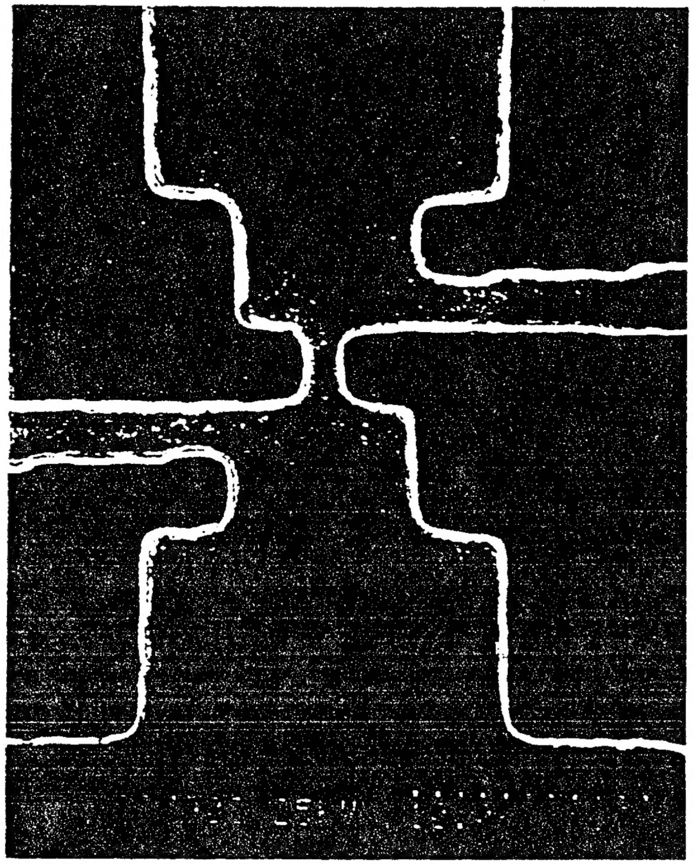
3. We have developed a new methodology for simulation of vortex arrays in which each vortex is itself treated as a statistical variable and the long-range logarithmic interactions are treated by summing up a series of image forces in the simulation sample with periodic boundary conditions. Studies of two-dimensional vortex lattice melting have been carried out by Seungoh Ryu using this representation. Application to an array made out of high Tc junction elements would require an extension in which the vortices moved in a heterogeneous geometry representing the array structure. This has not been done so far.

Currently we are studying the kinetics of vortices within this vortex variable representation using Kawasaki dynamics to simulate the damped motion of vortices in the presence of an external drive current. So far we have been able to simulate the nonlinear I-V characteristics expected for the motion of vortices in a dissipative medium. We expect eventually to write up a report on the results of these studies with possible applications to the modeling of junction array properties.

III. Publications

P. Rosenthal, M. R. Beasley, K. Char, M. S. Colelough and G. Zaharchuck, Appl. Phys. Lett. **59**, 3482 (1991).

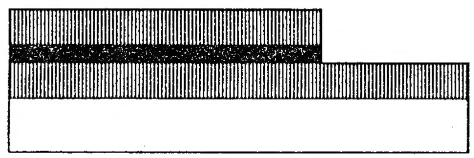
SEM image of a 0.5 μm wide by 1.0 μm long microbridge.



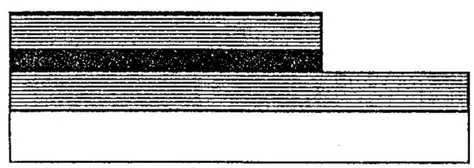
(wafer CB012 M1 N1)

Current passes thru the top and bottom leads.
The voltage across the microbridge is measured
with the narrow left and right leads.

Sandwich Junctions

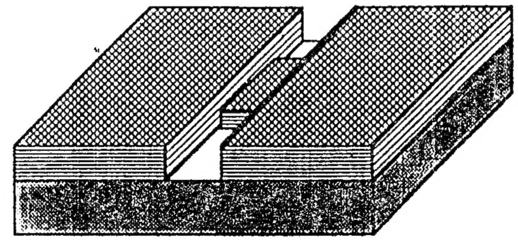


Classic sandwich
- a axis

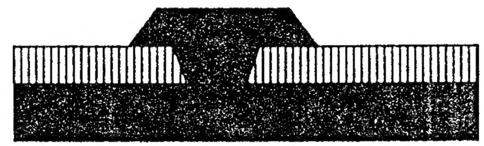


Classic sandwich c axis

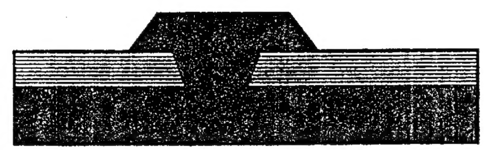
Planar SNS and Microbridge



Classic variable thickness
microbrige



Classic Planar
SNS
a axis film



Classic Planar
SNS
c axis film

Various Geometries of Classic Sandwich and Planar-Type
Josephson Junctions